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Review of Fatigue Management Technologies for Enhanced Military Vehicle Safety and Performance

by Scott Kerick, Jason Metcalfe, Theo Feng, Anthony Ries, and Kaleb McDowell

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14. ABSTRACT
Vehicle survivability is an important issue in today's military, especially considering that Soldiers frequently perform sustained military operations for extended periods and often with fractionated or no sleep. It is well-established that fatigue, whether due to acute or chronic sleep deprivation, extended time-on-task or the interaction between sleep- and task-related factors, is associated with neurocognitive performance decrements across a broad range of perceptual, cognitive and motor functions. Recent analyses have revealed that motor vehicle crashes account for nearly one-third of U.S. military fatalities annually, making motor vehicle accidents the leading cause of fatalities among U.S. military personnel. Although fatigue management technologies have been developed to monitor and mitigate driver performance decrements and have the capability to improve driver safety and survivability, there exists no gold standard system or set of design criteria for the development and implementation of fatigue management technologies (FMTs). Therefore, the objectives of this report are to review currently available and emerging FMTs and to identify potential solutions for near-term integration of existing technologies into active safety technology programs for military vehicles. The report also discusses emerging technologies and future research needs required to advance the current state of the art fatigue management technologies.

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review, fatigue, fatigue management technologies, physiological monitoring, vehicle survivability, Soldier-system performance, vehicle survivability

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Executive Summary

1. Problem

Degraded Soldier performance is an essential factor that can undermine Army efforts aimed at enhancing vehicle survivability. In particular, Soldier errors can lead to poor tactical decisions, which in turn might compromise an ongoing mission or, in the case of military drivers of both unmanned and manned vehicles, cause otherwise preventable accidents that might render a vehicle inoperable or, worse yet, lead to injury or death. Indeed, vehicle crashes account for approximately a third of all military fatalities each year. A leading cause of motor vehicle crashes is fatigue and, as such, research on fatigue detection and mitigation has been ongoing for decades and continues to be an active area of research and technology development.

Advances in vehicle- and human-sensing technologies, especially those that are designed to predict or detect fatigue, enable monitoring and mitigation of driver performance decrements. Such technologies, called "Fatigue Management Technologies" (FMTs), have been shown to significantly improve driver safety without being prohibitively expensive. For example, cost-benefit analyses have been done with lane departure warning systems, which are not specific to fatigue mitigation but are incorporated into current FMTs, and it was determined that this technology alone could avert perhaps even thousands of collisions and still net positive investment returns in a five-year product lifecycle[1]. Greater benefits may be realized both with technologies developed more precisely for fatigue mitigation and by application in military settings where rigorous standard operating procedures could be implemented to ensure deeper FMT integration across domains from Soldier training to mission planning and deployment. Thus existing and emerging FMTs provide a basis for technology development aimed at enhancing survivability for military systems. Indeed, if robust and reliable FMTs were to be deployed with crews serving in military vehicles, the potential impact on accident reductions, enhanced situational awareness, and overall crew performance could be quite profound.

2. Method

A literature and technology review was conducted to determine what options are available, or will soon be available, with respect to FMTs for consideration for near- and medium-term integration into active safety technology programs for military vehicles. Currently, the range of FMTs is broad and the array of existing systems encompasses the spectrum of maturity from commercially available to proof-of-concept or prototype systems. Moreover, new FMTs are emerging rapidly, with older technologies falling into obsolescence or being subsumed into more

[1]Houser, A.; Murray, D.; Shackelford, S.; Kreeb, R.; Dunn, T. *Analysis of Benefits and Costs of Lane Departure Warning Systems for the Trucking Industry*; Technical Report FMCSA-RRT-09-022; 2009.

advanced modern systems. Therefore, rather than providing a detailed analysis of all current systems, a taxonomy is described that characterizes the general types of approaches to the development of FMTs. The elements of this FMT taxonomy are then assessed with respect to two sets of criteria, representing partially overlapping military and scientific concerns, and the advantages and disadvantages of each type of system are discussed. Finally, specific systems are highlighted as exemplars of particular categories within this taxonomy and conclusions of recent reviews that include the summary of highlighted FMTs are summarized along with commentary regarding a vision of an appropriate FMT solution for future military applications.

3. Results and Discussion

Following the literature review, it was determined that fatigue monitoring technologies can be categorized according to their functional basis in one of three primary approaches, which include vehicle-centered, operator-centered, or hybrid/combination approaches. Vehicle-centered approaches provide the operational basis for any system that was designed to use data from (1) operator-vehicle or (2) vehicle-environment monitors; variables monitored include steering and lane-keeping, accelerating, braking, and encountering objects or other vehicles on the road. These vehicle-centered approaches operate in real time and thus have an advantage of detecting imminent increases in risk. However, these technologies also have the disadvantage of using measurements of variables that (a) rely on detection of increased risk when it is in progress rather than prediction of future likely risk increases and (b) only have weak to moderate correlations with fatigue, and thus, may introduce inappropriate mitigations when a driving behavior appears to be due to fatigue but is in fact necessary to avert an accident (e.g., a pedestrian on the road that requires a lane departure to avoid). Operator-centered approaches, on the other hand, include any system that utilizes data from human operators and can be further broken into three subcategories:

1. Biomathematical models of alertness.
2. Fitness-for-duty testing.
3. Online monitoring technologies.

Of these three types of operator-centered technologies, only the online monitoring has the potential to enable prediction of fatigue onset in real time based on immediate data reflecting the operator’s changing state. Biomathematical models and fitness-for-duty tests provide a much courser prediction of the onset of fatigue and/or fatigue-related increases in risk (projecting across hours or even days), but have the advantage of being rooted in the knowledge of relatively long timescale changes in physiological state due to circadian and homeostatic mechanisms that may be obscured on the shorter moment-to-moment timescales. Finally, hybrid approaches result in technologies that incorporate two or more of operator- or vehicle-centered approaches to provide a more comprehensive and, ideally, more robust system that overcomes weaknesses of any single technology used in isolation and, importantly, can account for the multitude of timescales required for accurate and reliable monitoring of fatigue and fatigue-related risk during operational performance.

As we built our understanding of the options available for integration of FMTs, we concluded that a phased approach would be preferred. Specifically, it is envisioned that near-term integration efforts would focus on a limited number of currently available and proven technologies.

Systems such as the ASTiD,[*] OptAlert,[†] and SafeTraK (Takata Corp., Tokyo, Japan represent an important combination of vehicle- and operator-centered technologies that could account for a broader array of fatigue induced performance issues than any one current system could manage on its own. In a second medium-term phase, then, integration of these types of systems into a single system, such as the Cognitive Assessment Tool Set [CATS], Operator Performance Laboratory, University of Iowa), appears to enable increased potential for achieving greater robustness and reliability across a broader set of environments and operators. Finally, across the long term, it is recognized that continued research, at both basic and applied levels, is required to make FMT systems achieve higher reliability, validity, sensitivity, specificity, adaptability, compatibility, and user acceptability. We conclude that more successful future approaches will be those that integrate and fuse a variety of data at each level from human physiology and behavior to vehicle motion and mission performance.

4. Rationale

Vehicle survivability is an important issue in today's military. Typical survivability technologies include armor, obscurants, jammers, signature management, etc. However, one of the most critical aspects of survivability is the performance of Soldiers operating vehicles. Degradation of Soldier performance can be associated with a range of issues from poor tactical decision making, which can lead to vehicles being seen and acquired, to fatigue- or distraction-impaired driving, which can result in accidents, render vehicles inoperable, and cause significant injury or death to Soldiers. In fact, recent analyses have revealed that motor vehicle crashes account for nearly one-third of U.S. military fatalities annually, including both privately owned and military motor vehicles, making motor vehicle accidents the leading cause of fatalities among U.S. military personnel.[2] Further, one of the leading causes of vehicle accidents is driver fatigue[3] and, consequently, considerable scientific and engineering efforts have been applied to this problem for several decades and continue actively today.

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[*] ASTiD is a trademark of Fatigue Management International; Birkenhead Wirral, U.K.

[†] OptAlert is a registered trademark of OptAlert; Melbourne, Australia.

[2] Krahl, P. L.; Jankosky, C. J.; Thomas, R. J.; Hooper, T. I. Systematic Review of Military Motor Vehicle Crash-Related Injuries. *American Journal of Preventive Medicine* **2010**, *38*, Suppl. 1, S189–S196.

[3] NHTSA. Traffic Safety Facts: Drowsy Driving. U.S. Department of Transportation: National Highway Traffic Safety Administration, DOT HS 811 449, 2011. http://www-nrd.nhtsa.dot.gov/pubs/811449.pdf (accessed 08/14/13).

In civilian driving, the National Highway Traffic Safety Administration (NHSTA) conservatively estimates that 100,000 police-reported crashes are the direct result of driver fatigue each year, yielding an estimated 1,500 deaths, 71,000 injuries, and $12.5 billion in monetary losses[3]. Approximately 168 million people in the U.S. have reported driving while feeling drowsy and about 37% of them actually have fallen asleep at the wheel annually.[4] Approximately 4% (11 million drivers) admit to having had an accident or near accident because of being sleepy or too tired to drive. The problem is even more pronounced in the professional truck driving industry, within which approximately 20% of safety critical events (including crashes and near-crashes) experienced by local/short-haul truck drivers included driver drowsiness as a contributing factor.[5] In general, human errors are to blame in approximately 96% of all crashes[6] and drowsiness increases the driver's risk of a crash or near-crash by at least a factor of four.[7] These issues are likely to be accentuated in military vehicle environments because Soldiers perform high-stress missions across many time zones around the world for sustained periods.[8] Risks imposed by responding to mission demands across multiple time zones can include deficits in attention and alertness and consequently, performance errors that are associated with insufficient sleep, irregular sleep/work schedules that interrupt circadian rhythms, or misalignment of the Soldier's circadian cycle with local time zones. Moreover, unlike most civilian and commercial driving, which are primarily concerned with mobility and safety, military driving often involves the additional concern of simultaneously maintaining local area awareness for the sake of security.[9] Performance of this additional security burden, e.g., dynamically maintaining full-spectrum awareness of the environment, has also been shown to be

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[3] See footnote 3, page ix.

[4] National Sleep Foundation. Facts and Stats. 2005. http://drowsydriving.org/about/facts-and-stats/ (accessed 08/14/13).

[5] Hanowski, R. J.; Wierwille, W. W.; Dingus, T. A. An On-Road Study To Investigate Fatigue in Local/Short Haul Trucking. *Accident Analysis and Prevention* **2003**, *35*, 153–160.

[6] Amditis, A.; Bimpas, M.; Thomaidis, G.; Tsogas, M.; Netto, M.; Mammar, S.; Beutner, A.; Mohler, N.; Wirthgen, T.; Zipser, S.; Etemad, A.; Da Lio, M.; Cicilloni, R. A Situation-Adaptive Lane-Keeping Support System: Overview of the SAFELANE Approach. *IEEE Transactions on Intelligent Transportation Systems* **2010**, *11*, 617–629.

[7] Klauer, S.; Dingus, T.;Neale, V.; Sudweeks, J.; Ramsey, D. *The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data*; NHTSA Report No. DOT HS 810 594; Virginia Tech Transportation Institute: Blacksburg, VA, 2006.

[8] Mitler, M. M.; Carskadon, M. A.; Czeisler, C. A.; Dement, W. C.; Dinges, D. F.; Graeber, R. C. Catastrophes, Sleep, and Public Policy: Consensus Report. *Sleep* **1988**, *11*, 100–109.

[9] McDowell, K.; Nunez, P.; Hutchins, S.; Metcalfe, J. S. Secure Mobility and the Autonomous Driver. *IEEE Transactions on Robotics* **2008**, *24*, 688–697.

susceptible to fatigue-related decrements,[10,11,12] which likely compounds the effects of fatigue on vehicle and Soldier survivability.

Recent technologies geared toward monitoring and mitigating driver performance decrements, referred to in the literature and in this report as Fatigue Management Technologies (FMTs),[*] have been shown to improve driver safety and survivability. For example, Houser et al.[1] evaluated the costs and benefits for industries associated with lane departure warning systems and concluded that motor carriers purchasing this technology will likely prevent thousands to tens of thousands of crashes and net positive returns on investments within a five-year product lifecycle for single-vehicle roadway departure crashes, same-direction lane departure crashes, and opposite-direction lane departure crashes. Support for this claim is evidenced by the adoption of lane departure and steering wheel tracking technologies in modern vehicle designs for commercial markets (e.g., Mercedes-Benz's Attention Assist system[13]) and, similarly, FMTs in the commercial trucking and transportation industries (e.g., OptAlert in the European trucking industry and the SmartCap in the Australian trucking industry). Within military environments, it is likely that even greater benefits could be realized because standard operating procedures could be implemented to ensure that these systems are more fully integrated into all aspects of Soldier training, mission planning, and operational performance. If such a system is deployed with crews serving military vehicles, the potential impact on accident reductions, enhanced situation awareness, and overall crew performance could be quite profound. In short, successful integration of FMTs has the potential for immediate impact on Soldier survivability and lethality.

5. Specific Objectives

A primary goal in developing FMTs is to enable prediction and subsequent mitigation or prevention of performance decrements before they occur. As a step towards enabling integration of FMTs into military test-bed vehicles, this report presents a review of currently available and emerging FMTs and identifies potential solutions based on these technologies that may be

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[10]Belenky, G.; Penetar, D. M.; Thorne, D.; Popp, K.; Leu, J.; Thomas, M.; Sing, H.; Balkin, T.; Wesensten, N.; Redmond, D. (1994). The Effects of Sleep Deprivation on Performance During Continuous Combat Operations. Marriott, B. M., Ed., In *Food Components to Enhance Performance*, National Academy Press: Washington, DC, pp. 127–135.

[11]Johnson, R. F.; Merullo, D. J. Friend-Foe Discrimination, Caffeine, and Sentry Duty. *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting*, 1999.

[12]Lieberman, H. R.; Niro, P.; Tharion, W. J.; Nindl, B. C.; Castellani, J. W.; Montain, S. J. Cognition During Sustained Operations: Comparison of a Laboratory Simulation to Field Studies. *Aviation, Space and Environmental Medicine* **2006**, *77*, 929–935.

[*]Here, our use of and reference to Fatigue Management Technologies (FMTs) is distinct from Fatigue Risk Management Systems (FRMS), which is a term typically used in reference to systems developed for and successfully applied in aviation, mining, and commercial trucking industries. FRMS most commonly refers to data and model-driven systems that are used to assist in designing work scheduling scenarios and performing subsequent predictive and retroactive analysis of their effects on fatigue-related risk at individual, fleet, and institutional levels. The purpose of the current report is to focus more specifically on the variety of technologies that may either be leveraged into larger FRMSs or employed as stand-alone mitigations of fatigue-related risks. Therefore, we distinguish these individual technologies using the general term FMTs.

[1]See footnote 1, page vii.

[13]Mercedes-Benz. Mercedes safety: Attention Assist, Pre-Safe & Distronic Plus. http://www.mbusa.com/mercedes/benz/safety (accessed 2013).

suitable for application in both near- and medium-term time frames. Moreover, emerging technologies, in particular, are discussed in terms of the need for continued FMT research and development across the long-term evolution of military active vehicle safety programs. This report also provides a large, though not fully comprehensive, reference to a broad range of fatigue and fatigue-related technologies available as of the date of publication. Because the range and number of solutions for fatigue management is quite large and varies considerably in technical maturity and sophistication, the aim of this report is to provide a concise summary and evaluation of general methodologies for developing FMTs rather than presenting a comprehensive system-by-system review and technology assessment. Basic information is presented, in summary form, for a variety of currently available commercial-off-the-shelf technologies as well as promising emerging technologies (see the appendix in this report). Gaps are identified that need to be addressed through current and future research efforts if FMTs are to have broad applicability and utility. Because of the differences with respect to military versus civilian applications, key constraints and concerns that must be considered for the application of FMTs in military environments are also delineated and discussed.

1. Enhancing Survivability with Fatigue Management Technologies (FMTs)

Modern concepts for mitigating shortcomings of complex technologies continue to include the presence of a human in the operational loop. The inclusion of human operators in the control loop for artificial systems is critical because humans have a capacity for learning and adaptation that lends robustness to systems that would otherwise fail, likely catastrophically, in highly complex and dynamic environments. The human, in a sense, acts as an additional sensor providing for more robust overall system performance. However, as with purpose-built technologies, humans are imperfect and often make errors in judgment and/or action selection, particularly while under stress, distraction, or fatigue. In the battlefield context, human errors are likely to compromise survivability. For example, misperception of vehicle position relative to the side of an unimproved or degraded road may lead to a rollover incident or, similarly, the momentary lapse of attention during a convoy operation may cause a rear-end collision. To the extent that system designers choose to neglect the development of mitigations for human error, there will continue to be an upper bound on the level of survivability that may be achieved in modern technically advanced Soldier-systems.

As has been well-established, many of the types of human errors that can reduce survivability in a vehicle-based context are attributable to fatigue-related impairment, which is partially amenable to mitigation or, at minimum, addressable through fatigue risk management approaches that include hours of service regulations such as those commonly implemented in commercial trucking and aviation industries. A more proactive technology-based solution, for example, would be safeguarding though the use of external vehicle sensors (e.g., video-based lane position detectors or sonar-based collision detectors) that enable intervention under circumstances where the fatigued human has neglected to perceive a need to correct vehicle motion. Yet, such an active intervention is known to provide for only an incomplete solution. It is known that in order for a new technology to be acceptable, it is critical to provide the operator a sense that they maintain a significant degree of control over the performance of their task or they will actively choose to disable or otherwise circumvent the new technology (Parasuraman et al., 2000). Thus while safeguarding technologies such as those involved in automated lane-keeping or collision avoidance may have an important role in enhancing survivability, they should be applied judiciously and as a limited part of a broader survivability-enhancement or risk management strategy. Another strategy is thus needed to help preserve the balance between allowing humans enough control to accomplish tasks in the way that they want to accomplish them and providing safeguards for circumstances where humans either could not respond appropriately or would otherwise choose a response that would lead to a catastrophic outcome (i.e., when a crash is imminent).

FMTs offer a promising solution for maintaining the balance between automated intervention and preservation of the operator's perception of control. Through adequate monitoring of the driver's level of fatigue or fatigue-related performance, it is possible to alert the driver to his/her own state and provide the opportunity to either change the current course of action or to decide to take a rest. Moreover, some concepts of FMTs have involved notions of adapting the in-vehicle environment when a fatigue state is detected so as to provide opportunity for the driver to continue performance without sacrificing control. For example, through the Assessment of driver vigilance and Warning According to traffic risK Estimation (AWAKE) project, that was active in the early 2000s, concepts were developed for increasing alertness in a fatigued driver by automatically introducing fresh or cool air into the cabin, providing additional stimulation through vibration of the seatbelt or steering wheel, or perhaps by playing an alerting sound (Bekiaris and Nikoloau, 2004). As applied in military-relevant circumstances, not only could such FMTs be applied to assist drivers and thus reduce mobility-based performance errors, but they could also be applied to crew members in nondriver roles (i.e., Commander, Gunner, Robotics Non-Commissioned Officer [NCO]) where other performance issues may arise as a result of increased level of fatigue. Tasks such as overwatch, local area reconnaissance, and operation of unmanned assets each could have their own mission-critical failures attributable to fatigue and these could likewise be addressed if appropriate technologies were integrated to detect and subsequently act to mitigate the effects of fatigue.

1.1 Concerns and Constraints

As yet, there exists no single, integrated solution that will work reliably for all task and environmental circumstances. As such, it is important to constrain discussions by defining the parameters and issues that are critical for success within the particular context for which the system may ultimately be developed. Therefore, considering the intent to examine technologies to enhance vehicle survivability in military operational environments, here FMTs are evaluated largely in terms of their suitability for near-term integration into military test-bed vehicles that are currently under development in an active vehicle safety program. This focus implies that the FMTs should be 'minimally-invasive' to the test-beds and not interfere with important safety and/or performance constraints unique to Soldiers and military driving. We have worked with military vehicle test-bed developers and identified the following constraints that must be addressed when considering potential integration of FMTs with test-bed vehicles. Specifically, military-relevant constraints dictate that to be applicable in test-bed vehicles FMTs should not:

- Interfere with a Soldier's capability to rapidly egress from the vehicle (e.g., technologies should not tether the Soldier to the vehicle)
- Pose an additional risk in the event of dynamic evasive driving maneuvers, near-crash, or crash incidents (e.g., hardware mounted to the vehicle should not cause injury in the event of an accident or rapid vehicle acceleration, braking or swerving, therefore FMTs requiring internal hardware mounts should be considered carefully)

- Require special or preconfigured steering devices or seats (because test-bed systems use commercial off-the-shelf steering devices and seats)

Other nonmilitary constraints and considerations of FMTs must be evaluated as well, including scientific and engineering criteria regarding performance and effectiveness, practical criteria for operator acceptance, and legal/policy issues (Balkin et al., 2011; Dinges and Mallis, 1998; Hartley et al., 2000). In the sphere of concern for scientists and engineers, the following criteria should be considered:

- Validity—does the system measure the fatigue or fatigue-related decrements it purports to measure?
- Reliability—does the system exhibit consistency in its measurement of these fatigue-related quantities or qualities over time?
- Generalizability—does the system equivalently measure the same fatigue-related event or even the construct of fatigue for all drivers equally across diverse environments?
- Sensitivity—does the system correctly identify true fatigue-related events?
- Specificity—does the system correctly reject false events that are not fatigue-related?
- Adaptability—does the system adapt to individual differences in susceptibility to the effects of fatigue and to changes in operators with extended use of the system?
- Compatibility—does the system function in a compatible manner with other operational or vehicle systems?
- Acceptability—does the system provide acceptable and trustworthy information/behavior and is it minimally invasive to the operator?

Given these constraints and considerations, we now review a taxonomy of approaches for understanding and assessing both existing and emerging FMTs.

1.2 Approaches/Types of FMTs

There currently exists no ‘gold standard’ set of specifications for either military or civilian FMTs. Consequently, numerous approaches and types of FMTs exist, and these technologies and methods apply differentially across diverse operational contexts and purposes. A table is provided in the appendix that lists all of the systems referenced in the following discussion as well as a number of other similar systems that are currently being competitively marketed (Attention Assist is not included in the table owing to its lack of commercial availability). In this table, primary technologies, capabilities, and conformance with constraints on integration with military test-bed vehicles are summarized for each FMT. Because this list is large and includes many redundancies as well as subtle distinctions between specific systems, it serves the following discussion as a reference rather than a point of focus. Here forth the discussion centers on description and evaluation of the general approaches adopted by FMT developers.

Approaches to the development and design of FMTs can be organized into three general categories that include vehicle-centered, operator-centered, and hybrid. This taxonomy is an adaptation of a set of four categories for FMTs that were initially presented by Dinges and Mallis (1998) and then used to frame other subsequent reviews on similar technologies (e.g., Barr et al., 2009; Hartley et al., 2000). Important to note, whereas here we distinguish vehicle-centered from operator-centered approaches based on the source data for the FMT, the initial categorization proposed by Dinges and Mallis (1998) considered all four broad technology categories to be "operator-centered," including vehicle-based performance technologies that founded their assessments, for instance, on measurements of steering wheel movement and/or vehicle motion characteristics. In our adaptation, we make an extra distinction by virtue of presenting vehicle-centered approaches that focus on the operator-vehicle monitoring as separate from those that focus on the vehicle-environment monitoring. With this exception, the remaining approaches, which we place under the rubric of operator-centered approaches, represent the same delineation as that originally made by Dinges and Mallis (1998) though our chosen category designations vary slightly. Figure 1 illustrates the current taxonomy, with gray boxes indicating the three general categories and open, dashed boxes indicating subcategories.

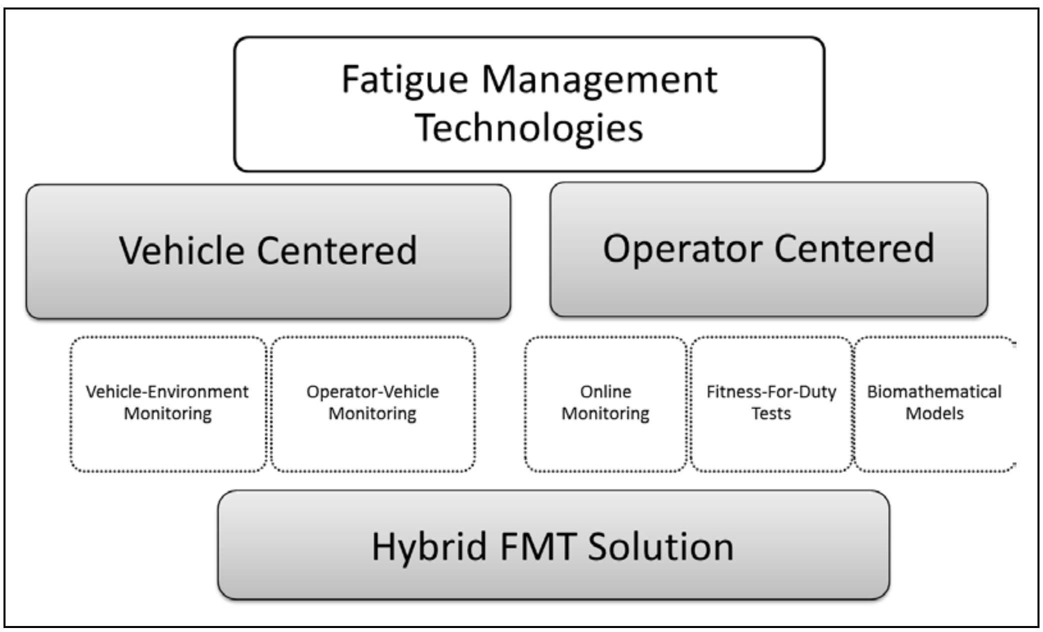

Figure 1. Illustration of the FMT taxonomy used as the focal point of discussion and analysis in this report.

It is also important to note that the majority of the approaches and systems discussed in this review do not make, or attempt to make, a distinction in performance degradation due to different sources or types of fatigue. By saying that there are different sources of performance degradation, we mean that, at the highest level, fatigue can be delineated as a set of mental and physical phenomena that are either associated with the physiological drive to sleep or with sustained expenditure of effort to perform a particular task. That is, fatigue may refer to performance detriments due to either sleepiness or time-on-task (Balkin and Wesensten, 2011; van der Hulst et al., 2001). Although these causes appear to be distinct, it remains an open question as to whether the changes associated with sleepiness and time-on-task are due to different mechanisms at the neurophysiological level. The potential importance of this knowledge is that, ultimately, there may be implications for targeting strategies for mitigation or intervention based on the source of the change in performance. However, in the main it seems that FMT development approaches tend to be agnostic to this issue. As a way to acknowledge this ambiguity and to provide a persistent reminder of it, we will refer to FMTs as being targeted at 'fatigue and fatigue-related phenomena' throughout the following discussion.

1.2.1 Vehicle-Centered Approaches

Vehicle-centered approaches can be defined as those that capture data from sensors that monitor dynamic states of the vehicle, vehicle components, or the environment in which the vehicle is operating. Vehicle-centered approaches can be further classified into two subcategories based on whether the sensors capture data from operator-vehicle or vehicle-environment interactions. Both approaches provide real-time measures for detecting or predicting performance decrements that are commonly, though not always uniquely, associated with fatigue or fatigue-related phenomena. Examples of vehicle-centered measures that have been used in the literature include the processing of steering inputs or vehicle position estimates to derive statistical descriptors such as the mean, variance, or spectral measures such as the modal frequency or signal power (refer to Table A.1, p. 349 in Forsman et al., 2013). Of the various options, some research has indicated that the information that comes from sensors that provide estimates of increasing variability in steering control is the most predictive of fatigue and fatigue-related performance deterioration (Forsman et al., 2013; Sandberg et al., 2011). Some have supplemented such steering-based metrics with either spatial or spectral (especially increasing power in very low-frequency ranges) estimates of increasing lane position variability and found an enhanced ability to predict onset of fatigue-like symptoms (Forsman et al., 2013; Mattsson, 2007).

1.2.1.1 Operator-Vehicle Interactions

Systems for monitoring operator-vehicle interactions include steering wheel movement sensors, steering wheel grip pressure sensors, and sensors for monitoring acceleration, gear-shifting, and braking. The success of such metrics is attested to by the integration of steering-based prediction into the commercially-available "Attention Assist" technology offered in Mercedes-Benz E-Class models. That is, though the Attention Assist system monitors 70 parameters related to driving performance and environmental conditions, it is the operator-vehicle interaction, steering performance that has been selected by engineers as the primary variable that yields the earliest prediction of fatigue onset. This successfully-implemented, operator-centered system then uses decision logic based on the sensed steering patterns as compared with a baseline driver profile taken in context of the other parameters (such as crosswind strength, road smoothness, and other operator-vehicle interactions) to determine whether an intervention would likely be useful or even critical (refer to Mercedes-Benz, 2013).

1.2.1.2 Vehicle-Environment Interactions

Examples of vehicle-centered systems that monitor vehicle-environment interactions include those based on lane deviation sensors, inter-vehicle distance sensors, and time-to-contact/object-avoidance sensors. The Takata SafeTrak Systems (Takata Corporation, Tokyo, Japan), for instance, use forward-looking digital video and image processing to monitor vehicle position relative to lane markings along the road and, when necessary, provide a warning triggered by vehicle drifting out of the lane or by vehicle behavior that resembles drowsy driving (i.e., increased variability in lane maintenance that indicates ongoing swerving). More specifically, the SafeTraK 1++ system continuously monitors signaled versus unsignaled lane changing behavior and quantifies both as drifts that are defined as crossing a dashed or solid lane boundary. Additionally, the system calculates time spent outside of the lane during a drift and it differentiates between large (>18 in) and small drift amounts (TK Holdings, 2008). Use of such variables then allows the system to selectively alert the driver only in cases where it seems that the lane deviation behavior is unintended and therefore a likely indication of inattention or fatigue. The company claims that such lane departure warning technologies reduce lane excursions by 50% and decrease single-vehicle road departure crashes and rollover crashes by 20% and 24%, respectively (Takada Corp, 2009), statistics that are supported by and similar to those presented in a cost-benefit analysis performed by the U.S. Department of Transportation, Federal Motor Carrier Safety Administration (Houser et al., 2009).

1.2.1.3 Conformance with Constraints on Application to Military Vehicles

As previously mentioned, many FMTs appear to be agnostic to the question of whether they actually index driver fatigue. This is particularly true for vehicle-centered approaches which, as presented, are limited to monitoring vehicle behaviors that, at best, have been correlated with increasing risk of accident or injury. Yet, while these approaches are not initially (or exclusively) designed for fatigue management or mitigation, they have yielded off-the-shelf safety technologies that are among the most mature that are currently available. As such, vehicle-centered technologies are available for immediate integration as components of an FMT system. Advances in video and infrared sensors, ultrasound, LADAR, SONAR, and global positioning systems contribute to lane keeping support and collision avoidance and may be leveraged as safeguarding mechanisms into FMT systems.* Moreover, the implementation of such safeguarding technologies has been shown to improve operator performance in online monitoring of manned semiautonomous vehicles while simultaneously enabling the performance of additional security tasks including monitoring and planning for external autonomous assets and maintenance of local area awareness (McDowell et al., 2008). Summarily, then, vehicle-centered systems tend to comply with the military-relevant constraints presented above because most use existing in-vehicle sensors and thus do not require steering wheel or seat modifications, mount hardware to the exterior of the vehicle rather than its interior, and they do not require sensors that tether operators within the vehicle or otherwise interfere with driving performance or safety. Perhaps more importantly, they have been shown to enable greater capabilities while preserving safe control over manned semiautonomous assets.

1.2.1.4 Advantages/Disadvantages of Vehicle-Centered Approaches

The major advantages of vehicle-centered approaches are that they are currently mature, they are nonintrusive, and they are often designed to make use of existing vehicle sensors or data (i.e., they capture embedded performance measures). Moreover, as long as they do not interfere with vehicle control, humans tend to prefer vehicle-centered over operator-centered technologies because the latter are often perceived as more of an invasion of privacy (Dinges et al., 2005).

The major disadvantages are that vehicle-centered FMTs are not typically robust across different vehicle types, weather conditions, road characteristics, lane markings (or lack thereof), traffic patterns, and individual differences in driving habits and tendencies. Therefore, while these technologies tend to deal with the military-relevant constraints in an appropriate manner, they do not necessarily meet the more rigorous scientific and engineering requirements such as validity, reliability, generalizability, and adaptability, thus limiting the breadth of their immediate applicability across the diverse range of operational conditions and tasks involved in typical military applications. In particular, validity of vehicle-based approaches is limited in that they rely on monitoring variables, such as steering wheel position variability, lane position variability, lane departures, and obstacle proximity, which are only indirect correlates of fatigue rather than direct measures of the state of the operator. Moreover, some evidence has shown relatively low, but significant rates (14%) of false positives (Eskandarian et al., 2007), thus reducing reliability and potentially impacting operator trust.

Finally, such technologies are constrained in current implementation because they are often designed specifically for highway driving. Thus, such systems are less generalizable and adaptable as they currently exist because they tend not to work at lower speeds, on roadways

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*Several types of technologies have been developed for lane departure warning and lane keeping support systems. Examples include monocular video sensors (Clanton et al., 2009), laser scanners (Kirchner and Heinrich, 1998), high-resolution radar (Polychronopoulos et al., 2004), infrared cameras (Cheng et al., 2006; Fardi and Wanielik, 2004), GPS sensors (Clanton et al., 2009; NHTSA, 2003), and systems that integrate two or more of these technologies (e.g., the European Union's SAFELANE and PReVENT projects [Amditis et al., 2008, 2010]).

where lane markings are absent, or in environmental conditions (e.g., snow, mud, ice, heavy rain) that lead to obscuring the view of the lane markings and/or, in the case of video-based technologies, reducing visibility of the lenses of the sensors themselves (refer to U.S. Department of Transportation in the references).

1.2.2 Operator-Centered Approaches

Operator-centered approaches can be defined as those that capture data from humans before or during operational performance. These technologies can be classified into three subtypes that include: (1) biomathematical models based on circadian cycles and various homeostatic sleep/wake timing factors, (2) fitness-for-duty tests that use assessments of pretask performance and/or physiological state to assess readiness to perform, and (3) online monitoring technologies involving dynamic acquisition and processing of human data concurrent with operational performance across a variety of time intervals. Of these subtypes, the first two are not designed for detecting or predicting real-time changes in alertness, fatigue, or fatigue-related risk but rather provide longer-term predictive approaches on time scales ranging from hours to days. Biomathematical models and fitness-for-duty tests are typically employed before or during interruptions in operational performance to predict or determine present readiness and/or to estimate the extent to which decrements are likely to occur later during operational performance under particular schedule constraints. Finally, and unlike the other two approaches in this category, the third type of operator-centered FMT provides online fatigue or fatigue-related performance estimates that are updated at time intervals that can vary from seconds to tens of minutes. Because the online approaches enable acquisition and processing of human-generated data from one or more sensors during operational performance, they can be used to detect or predict immediate or impending levels of risk. When increased risk levels are detected, then these online FMTs may trigger a warning to the driver and/or an external supervisor as well as activate other automated mitigations, such as those described above as vehicle-centered technologies.

1.2.2.1 Biomathematical Models

Biomathematical models use, in a variety of combinations, information about an individual's recent sleep history, duration of wakefulness, and work/rest patterns as inputs to calculations that incorporate general knowledge of circadian phase and homeostatic mechanisms to predict a variety of performance metrics, such as effectiveness or alertness, over a projected work shift or duty cycle (Barr et al., 2009; Dawson et al., 2011; Hursh et al., 2004b). Typically these models are the core of larger Fatigue Risk Management Systems (FRMS) that are used to design and evaluate work/rest schedules, plan work and sleep shifts during prolonged operational missions, assist in estimating the timing of countermeasures to anticipated performance deficits, and to develop accident assessment and policy-making strategies (Barr et al., 2009). These types of operator-centered approaches may also be used in retrospective evaluations of schedules to identify fatigue-related risk as well as in an approach that uses iterative assessment (along with or independent of other FMTs) to improve schedules by reducing exposure to times of impaired performance levels. An example of a biomathematical model of alertness in current use by the U.S. military and commercial transportation industries is the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model* that has been applied to a Fatigue Avoidance Scheduling Tool (FAST) for flight crews. Initial examinations of the SAFTE model aimed at its validation accounted for approximately 98% of the variance in data sets derived from individuals performing standard laboratory tests of cognition (Hursh et al., 2004a,b) and 93% in a data set from real accident rates in the railroad industry (Hursh et al., 2006).

1.2.2.2 Fitness-for-Duty Tests

Tests of fitness for duty are typically administered in the form of a simple auditory or visual reaction time task (e.g., the psychomotor vigilance task [PVT] [Dinges and Powell, 1985]) before a work shift begins. Results of such tests provide a distribution of reaction times, from which decisions can be made about a person's current level of alertness and thus whether one is fit for duty. The PVT is perhaps the most widely used of these types of tests, in large part because of its sensitivity to sleep-deprivation (Dorrian et al., 2005; Drummond et al., 2005) and time-on-task effects (Doran et al., 2001; Lim et al., 2010). Similar relations, however, are not as well understood for other sources of fatigue-related performance changes, such as declining motivation or prolonged exposure to stressors (heat, operational tempo), and thus standard fitness-for-duty assessments may require supplementation by other methods. Other physiological or behavioral assessments have been established as viable options; for instance, measures of ocular behavior such as eye reflexes, pupil diameter, latency and amplitude of pupil response, and saccadic velocity tests are effective for detecting pre-task performance impairment (Hartley et al., 2000).

1.2.2.3 Online Monitoring

Online monitoring technologies are used to continuously record behavioral or physiological responses of human operators concurrent with their task performance over the course of a work shift or duty cycle. These FMTs are designed to detect or predict early decreases in alertness or decrements in performance before an accident or catastrophic incident occurs. Such technologies can be further subdivided into direct-contact and non-contact approaches in terms of the manner by which data from humans are acquired (Lin et al., 2005). Direct-contact approaches require direct contact of sensors to the human body to record behavioral or physiological data (e.g., electroencephalography [EEG], electrocardiography [ECG], electromyography [EMG], galvanic skin response [GSR], respiration, temperature, body movement kinematics, etc.), whereas noncontact approaches use optical sensors or video cameras mounted on a dashboard, windshield, rear-view mirror, or other vehicle component to record behavioral or physiological

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*See also the U.S. Army Sleep Management System, which was designed to integrate sleep timing and quantity data with a mathematical model of alertness as a means of optimizing work schedules (Belenky et al., 1998).

data (e.g., eye tracking systems[*] to obtain measures of head nods, facial expressions, eye movements, eye blinks, eye closures, eye gaze patterns, pupil diameter, limb movements, and posture).

Online monitors may operate across a range of time intervals. For example, EEG (e.g., the Epoc, B-Alert, and SmartCap) and eye feature detectors (e.g., Driver Fatigue Monitor MR688, OptAlert,[†] OpGuard) record data continuously and are capable of making near instantaneous assessments of fatigue risk. Other systems, however, use simpler technologies that poll operators across longer random intervals (10–20 minutes). For instance, systems like the Muirhead[‡] Fatigue Warning System or the Ctrack Random Reactive Fatigue Warning System use a simple attentional probe (such as a light that appears on the dashboard) that must be responded to within a short period of time before a fatigue state is considered to have been detected and an alert is triggered. It is important to note, however, that because of the time intervals used in these latter types of technologies, the likelihood of missing a fatigue state increases. That is, with the real-time or near real-time systems, fatigue risk can be assessed near instantaneously or even predictively whereas the systems relying in discrete probes (and similarly, head nod detectors like the Nap Zapper) are only likely to catch fatigue that has already onset, which may be too late for enabling effective countermeasures.

1.2.2.4 Conformance with Constraints on Application to Military Vehicles

As compared with vehicle-centered approaches, operator-centered approaches as a whole (real-time monitoring approaches in particular) are less suitable for immediate integration into active vehicle safety programs. In large part, the lack of readiness of operator-centered FMTs is because they currently do not adequately address either the constraints on integration into military environments or the additional science and engineering criteria. Of the subtypes of operator-centered approaches, biomathematical models and fitness-for-duty tests may be more suitable for immediate integration because they do not require additional physical sensors or other physical equipment that would interfere with the Solider; though, their applicability would be constrained by limited actual predictive validity and generalizability, particularly across individual differences (Dinges, 2004). Online monitoring approaches, on the other hand, present additional challenges for integration in military environments because they tend to require direct-contact sensors to be applied to operators and these sensors and any associated cables may tether the operator to the vehicle, depending on the implementation (i.e., wired versus wireless systems). Moreover, such real-time monitoring systems may also require internal mounts in terms of dashboard cameras for detecting head, body, or eye movements, and these cameras could pose a threat to safety in the event of a crash or evasive driving maneuvers should they

[*]It should be noted that some eye monitoring technologies (e.g., OptAlert) are mounted on eyeglass frames and thus could be considered direct-contact sensors.

[†]OptAlert is a registered trademark of OptAlert; Melbourne, Australia.

[‡]Muirhead is a registered trademark of Remote Control Technologies, Pty. Ltd.; Perth, Australia.

become dislodged. However, with continuing advances in wireless sensor systems and miniaturization of hardware components (e.g., Liao et al., 2012; Lin et al., 2010), there is good reason to be optimistic that FMTs based on these systems will become much more feasible and ultimately able to more adequately address the constraints on military integration in the near future.

1.2.2.5 Advantages/Disadvantages of Operator-Centered Approaches

Advantages of biomathematical models and fitness-for-duty tests are that they can be used to optimize schedules and to predict performance hours or days prior to starting a shift and, as such, have a broad array of potential areas of application. For example, a priori assessments can just as easily apply to work scheduling as they can be used in combination with other real-time or near-real-time variables (either operator- or vehicle-centered) to enhance identification of fatigue or fatigue-related states in which performance deterioration would be predicted. Disadvantages include their relatively low-predictive accuracy, particularly as concerns the ability to predict variations across individuals (i.e., due to individual differences), which has been shown to account for greater than 50% of the variance in observed data (Van Dongen et al., 2011). That is, despite encouraging and positive conclusions such as those seen with the SAFTE/FAST model previously described, caution is justified because, as Dinges (2004) warned, most biomathematical models appear to be based on a general curve-fitting approach rather than on truly prospective and generative process-oriented (i.e., mechanistic or causal) methods. Additionally they are not designed for real-time monitoring, which means that they are limited as standalone technologies. Advantages of online operator-centered approaches, on the other hand, are that they can provide the most direct measures of immediate operator behavior and physiology and these measures are probabilistically associated with fatigue-related performance decrements. One EEG-based system, for example, was shown within a small sample (n = 10) of truck drivers to have reasonable performance in predicting fatigue while keeping the error rate around an encouraging 10% (Lal et al., 2003). Moreover, such online approaches are commonly based on sensors that have been developed to be lightweight and portable, thus opening an opportunity to provide advanced wearable biometric systems that could be ultimately fieldable in real-world dismount operations. Therefore, online operator-centered approaches fill a distinct gap where both vehicle-centered and the other operator-centered approaches fall short. That is, vehicle-centered approaches provide only indirect data that may be correlated with fatigue, but can be confounded by other factors, whereas most currently-available operator-centered approaches cannot provide the real-time resolution needed for immediate intervention. Disadvantages are that most of the current real-time implementations of operator-centered, online monitoring approaches require use of sensor systems that are often uncomfortable and intrusive to operators as just discussed. More of a challenge for these real-time and near real-time online systems is that the complexity and variability of biological signals is such that their momentary changes may not always provide unambiguous estimates of fatigue or fatigue-related factors that affect performance because they are known to be influenced by many factors and individual differences.

1.2.3 Hybrid Approaches

Carefully considered integration of one or more of the current technologies into an active vehicle safety program is likely to significantly lower the probability of crashes and save lives. As reviewed, each of the approaches already discussed have unique sets of advantages and disadvantages. Vehicle-based methods have matured the most rapidly, even to the point where they have been integrated into vehicles that are sold to the general public, yet they are limited in that they do not directly assess the state of the operator but rather infer the state based on correlated variables, which can influence the rate of false positives and likewise reduce operator trust. At the other end of the spectrum, are the operator-centered methods, such as biomathematical models and fitness-for-duty tests that are challenged to adequately deal with individual differences, but also lend a degree of both advance prediction of the likelihood of fatigue-related incidents as well as an ability to iteratively assess and tune systems over repeated uses. Ultimately, as sensors are moved both spatially closer to (or even on) the fatigued individual as well as temporally closer to the onset of the actual fatigue state, predictive ability begins to increase, particularly as pertains to the problem of individual variation. This suggests a logical (and currently theoretical) ideal entailing a solution that would involve combinations of FMTs that are designed to exploit the strengths of each and offset their individual weaknesses.

Hybrid approaches incorporate two or more types of technologies to provide a more comprehensive and robust system than any single technology used in isolation. A good example of a hybrid system is the Advisory System for Tired Drivers (ASTiD[*]), which is based in a combination of both operator- and vehicle-centered approaches (Caterpillar Safety Services, 2008; Golz et al., 2010). In support of this argument, there is research to suggest that a holistic, multisensor, hybrid data fusion approach with redundant integrated systems would be the most optimal solution for real-world FMTs (Balkin et al., 2011; Coetzer and Hancke, 2009; Ji, 2003; Ji et al., 2004, 2006). For instance, one pilot study of U.S. and Canadian truck drivers who were using concurrent vehicle- and operator-centered FMTs showed significant decreases in amount of eye closure and vehicle lane variability along with increases in estimated alertness (Dinges et al, 2005). Although a successful performance of such a combined system is encouraging, lack of comparison with individual technologies limits the ability to make conclusive statements in favor of more complex and likely more expensive hybrid systems. Currently, the most promising hybrid methods appear to be those that integrate lane departure warning systems with measures of ocular behavior such as the amplitude-velocity ratio of eye blinks and the percentage of eye closure (PERCLOS) over time because these measures have been shown to be the most valid and

[*]ASTiD is a trademark of Fatigue Management International; Birkenhead Wirral, U.K.

reliable indicators of fatigue and the least intrusive to drivers (Dinges et al., 1998; 2005; Johns et al., 2007; Vadeby et al., 2010; Wierwille, 1994). Future research is needed, however, to progress beyond theoretical and analytic assertions and to test and validate the promise of hybrid methods through direct comparisons of individual technologies against systems comprising various combinations of vehicle- and operator-centered technologies.

2. FMTs for Near- and Medium-Term Integration

In this section we identify FMTs that have significant potential for near- and medium-term integration into an active military vehicle safety program. We provide a brief review of aftermarket commercially available FMTs that we identified using a variety of sources, including the peer-reviewed literature, the World Wide Web, and personal communications with scientists, engineers, and other system developers. Although some of the technologies that we found have been evaluated in the open literature, many are proprietary and thus have been commercially marketed, installed in modern vehicles, and/or used by transportation industries without full public disclosure of information that would allow comparative assessment and evaluation. That is, for many FMTs that are currently available, very little information can be obtained regarding either their operational principles or the extent to which they have been evaluated for validity, reliability, sensitivity, and so forth. In the discussion that follows we provide a focused summary that highlights key findings from the most comprehensive reviews of commercially available and emerging FMTs that were published within five years prior to this report (i.e., Barr et al., 2009; Caterpillar Safety Services, 2008; Edwards et al., 2007; Golz et al., 2010; Wright et al., 2007). We acknowledge that, due to previously discussed issues of intellectual property protection, any such review will be inherently incomplete. Therefore, after our review of current and emerging technologies, we conclude with discussion of a need for further research and development in the domain of real-world FMTs. For older reviews and greater depth of history regarding FMT development, we also recommend Barr et al. (2005); Dinges et al. (2005); Hartley et al. (2000); Heitmann et al. (2001); Williamson and Chamberlain (2005).

2.1 Commercially Available FMTs for Near-Term Integration into Vehicle Test-Beds

Wright et al. (2007) assessed 48 different FMTs at various stages of maturity. Of the technologies that were reviewed, 15 were identified as worthy of further evaluation and, as of the completion of the current report, only five were confirmed to have remained available and/or under continued development. The currently available FMTs from the Wright et al. (2007) review included Seeing Machines faceLAB (now called the Driver State Sensor [DSS]), OptAlert, Smart Eye Pro (now available as the Smart Eye AntiSleep), Fatigue Management International's

ASTiD, and SafeTRAC (now marketed as SafeTraK 1++ and SafeTraK 3 by Takata Corporation). Ultimately Wright et al. (2007) concluded that, at the time, there were no commonly accepted methods for fatigue detection in realistic settings, but operator-centered approaches utilizing measures of eye movements/blinks and models of alertness were promising, especially if integrated with vehicle-based measures such as steering activity or lateral vehicle motion (i.e., a hybrid approach).

In a later review of 22 FMTs that was conducted by a panel of experts assembled by Caterpillar Safety Services (2008) (see also Golz et al., 2010), only three systems were deemed ready for implementation in operational environments. The three systems included ASTiD, HaulCheck,* and OptAlert. A caveat regarding the HaulCheck system, however, was that it was purpose-built and thus limited to applications in the mining industry where physical vertical lane markers and sensors demarcating roads to and from mining sites were always present, which is not the case in general use road networks (note that the Takada SafeTraK systems also rely on lane markings). More importantly, the HaulCheck system was designed to only take corrective action after the vehicle deviates dangerously out of its lane. Therefore, the HaulCheck system should not be recommended as a general use FMT, particularly for standard roadways and is therefore not included in the appendix. In the same review, Caterpillar's panel of experts evaluated two other operator-centered systems (faceLAB and the Driver State Monitor) and indicated that both were promising, but appeared to require further development before they could achieve robustness in realistic environments. As such, the ultimate conclusion by Caterpillar's panel of experts was a recommendation in favor of implementation of the ASTiD and/or the OptAlert system.

On the basis of these recent reviews, as well as current commercial acceptance, three systems stand out as most likely to provide utility as a near-term solution for fatigue risk mitigation in operational environments: ASTiD, OptAlert, and Takada SafeTraK or a comparable lane departure warning system (e.g., Mobileye, AutoVue–see the appendix). The first system, ASTiD (Fatigue Management International; Birkenhead Wirral, U.K.), is a hybrid system that integrates a component that provides hourly predictions of the likelihood of falling asleep over a 24-h period (an operator-centered approach implementing biomathematical modeling) with gyroscopic signal processing of steering inputs to infer patterns that resemble monotonous and/or sleepy driving (a vehicle-centered approach monitoring operator-vehicle interactions). The second system, OptAlert (OptAlert; Melbourne, Australia), is an eyeglass-mounted video-based infrared system that derives the commonly-used PERCLOS measure, gaze distribution, blink rate, and other eye blink/movement measures (an operator-centered approach using real-time monitoring) to infer fatigue states. The third system, the Takata SafeTraK (Takata Corp., Tokyo, Japan), is a lane departure warning system that combines video with machine vision software to watch the road

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*HaulCheck is a trademark of AcuMine Pty; Australia.

ahead and warn drivers if they unintentionally leave their lane, or if their driving pattern becomes erratic (a vehicle-centered approach monitoring vehicle-environment interactions). Although we consider these three highlighted systems to be good candidate solutions at this time, other comparable FMTs exist and are currently available (see the appendix). Thus, systems with capabilities similar to those highlighted above should also be considered, especially as pertains to the potential for combining or leveraging multiple systems for improving performance across individuals and environments as discussed in the following.

Here, we argue that though a single FMT that is broadly applicable across individuals and environments has yet to be developed, there are situations, such as military vehicle safety testing, in which conditions allow for definite near-term utility for specific commercial off-the-shelf technologies. Beyond the potential near-term integration of one or more of the systems highlighted in our review (ASTiD, OptAlert, or Takata SafeTraK), we also consider a significant medium-term potential of combining the important functional elements of these three technologies into a single hybrid system. Such an approach would capitalize on the strengths and offset the weaknesses of each individual system. For instance, as has been done in the AntiSleep Pilot (see the appendix), biomathematical modeling could be employed to predict periods of sleepiness, perhaps setting context for real time inference of other variables derived from direct, online monitoring of the operator for individual signs of fatigue as well as those derived from monitoring the vehicle to enable continuous assessments of a potentially imminent need for intervention or mitigation (i.e., due to an impending lane departure or collision). Moreover, initial fitness-for-duty tests could be used as part of an initialization of the biomathematical model used, allowing for further tightening of the variance due to individual differences. Capitalizing on the strengths of each method and technology in this way would enhance robustness and reliability and, ultimately, increase the breadth of circumstances under which FMTs could be made useful. One example of how such an optimal hybrid system could be conceived is provided in the high-level graphic presented in figure 2. Here, we see that safeguarding may be incorporated through vehicle-based technologies and, simultaneously, combinations of methods including both vehicle- and operator-centered methods not dissimilar from those just described could enable more robust state prediction and monitoring to provide enhanced ability to improve driver recognition of the imminent need for risk mitigation techniques.

2.2 Emerging FMTs for Medium-Term Integration and Beyond

Initial analyses have predicted considerable improvements in driver safety with FMTs, suggesting that immediate benefits to military vehicle survivability can be achieved through integration of systems such as those highlighted in the previous section. Yet, as also mentioned in the previous section, there remain areas in which even the most mature FMTs can be improved. Because of this, the modern focus of FMT development, as revealed in emerging technologies, shows a move toward adoption of more holistic methods that combine multiple vehicle- and operator-centered approaches into improved hybrid systems. Such approaches leverage a greater variety of available data sources, particularly looking more closely at the types of data that can be recorded from the human operator.

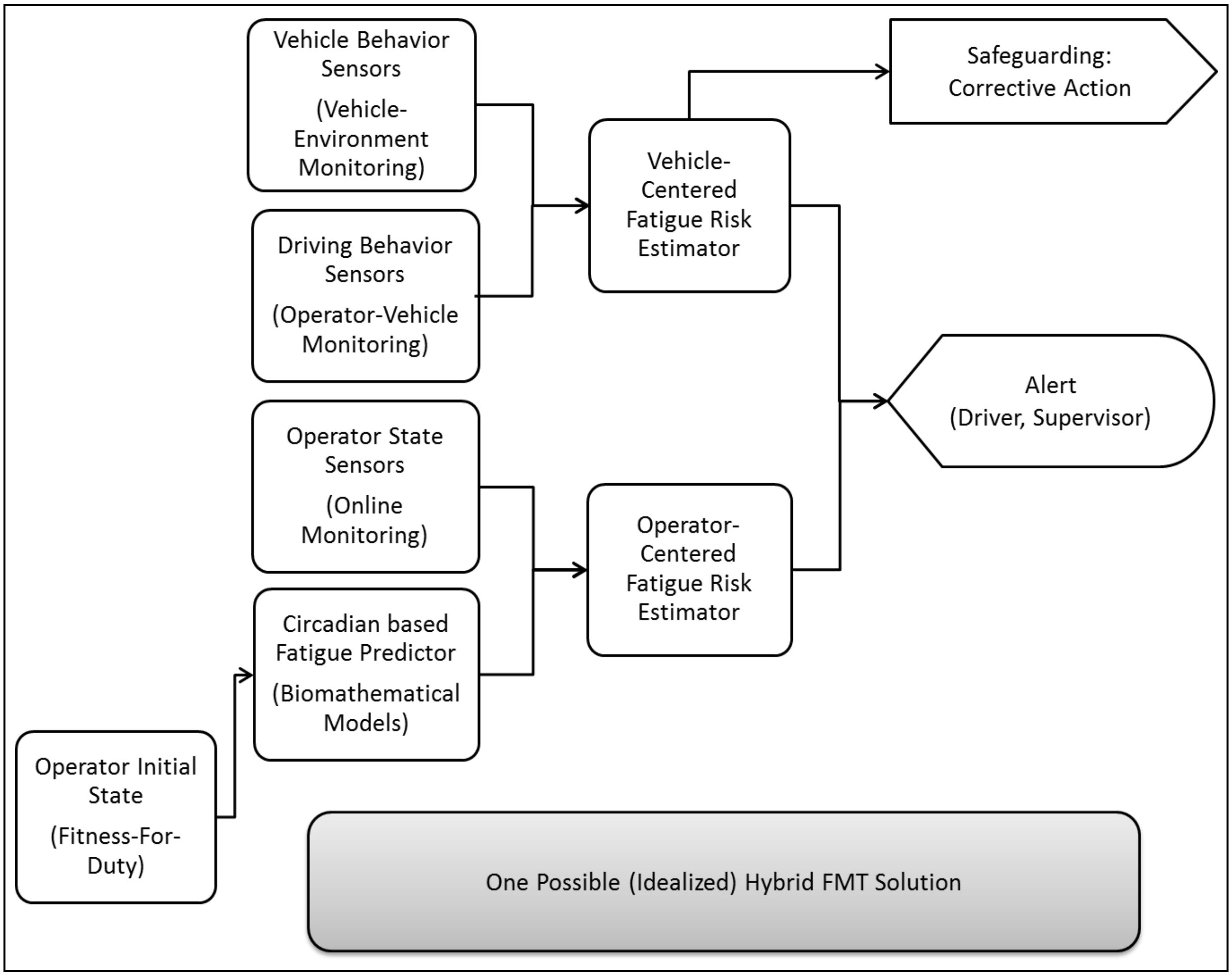

Figure 2. A schematic of one possible combination of existing FMT solutions to enable a hybrid system with increased robustness through adaptive safeguarding and enhanced means of providing predictive fatigue estimates that, using online measures as well as assessments of initial states, account for the hard problem of individual differences.

Here, we consider the inclusion of data recorded directly from the human operator as an important way to improve the precision and timing of future FMTs. That is, use of joint physiological and behavioral data taken from the operator can serve to remove ambiguity and facilitate the more precise identification of fatigue (and other cognitive) states. Further, because physiological changes precede the onset of different cognitive states, including fatigue, such data has the potential to provide additional temporal advantages by enabling prediction and mitigation of performance decrements before they could be sensed in vehicle-based technologies. Currently, both brain activity (EEG) monitoring and eye feature detection are emerging as important in modern efforts to develop operator-centered real-time monitoring FMTs.

Emerging EEG-based FMTs such as the Mindo (Brain Research Center, National Chiao Tung University, Taiwan), Quasar DSI 10/20 (Quantum Science and Applied Research, Inc.; San Diego, CA), and the B-Alert systems (Advanced Brain Monitoring, Inc.; Carlsbad, CA) use advanced, lightweight sensors and sophisticated signal processing techniques to wirelessly record and analyze brain activity in real-time and then make predictions of fatigue states. The progressive reduction in sensor size and weight in combination with the advancing quality of dry, wireless sensor and signal processing technologies enables mobile brain-imaging applications in ways previously not allowed by comparable gel-based, wired EEG systems. The advent of wireless sensors also alleviates a major concern regarding the tethering of Soldiers to vehicles, which is a strong advantage. However, current EEG sensor arrays continue to be uncomfortable to wear for long periods of time. More germane to the issue of survivability, these commercial wireless EEG systems are still not at a point where they can be worn safely and unobtrusively inside helmets under real operational conditions, although an effort is currently underway at the U.S. Army Research Laboratory (ARL) to address this specific issue through the development of soft electrodes (McDowell et al., 2013). Thus far, a prototype array of soft and stretchable EEG sensors embedded in a flexible substrate has been produced for initial assessment with military helmets. Finally, necessary progress is continuing on both basic and applied science levels to continually improve the ability to unambiguously infer cognitive states such as fatigue from brain data as well as to enhance the reliability and usability of EEG in real-world environments.

Similar to the advances seen in emerging EEG-based FMTs, those that are based in the detection and analysis of eye features are also enjoying continued popularity. Well-established systems for eye tracking, such as the DSS (Seeing Machines, Inc.; Tucson, AZ), Smart Eye AntiSleep (Smart Eye AB; Göteborg, SE), and the SMI Eye Tracking Glasses (SensoMotoric Instruments GmbH; Teltow, DE), while not designed for exclusive use as FMTs, have long been applied to basic and applied research in fatigue in general as well as driver fatigue in particular (refer to Dinges et al., 1998). Eye tracking systems are attractive because, unlike other methods of physiological monitoring, they do not absolutely require the placement of sensors on the body. Yet, as with the EEG-based technologies, these systems continue to require development before recommendations can be made regarding integration into military vehicle systems. A main concern is that eye and face tracking technologies require external cameras to be aimed at the face and eyes; the most common solution is the use of external cameras mounted in the environment (e.g., on the dashboard), but some solutions exist that are mounted on or integrated with the frames of eyeglasses (e.g., OptAlert, SMI Eye Tracking Glasses). Of course, neither of these solutions fit the current constraints on integration with military vehicles—one violates the constraint that additional sensors cannot be mounted in-vehicle and the other would need to be integrated with an already growing array of equipment that Soldiers must wear on their heads. Additionally, practical experience in using eye tracking technologies has revealed limitations on validity and reliability as well. For instance, with some systems that operate based on infrared illumination of the eyes, wearing eyeglasses leads to distortions in the recorded estimates of eye features. A further example is that, with typically fixed camera locations, the performance of these technologies tends to break down when the person being observed makes large head movements or otherwise obscures their face (e.g., using their hand to wipe sweat off of their brow).

Therefore, even with the current high degree of maturity and reliability of eye tracking systems for laboratory applications and on the commercial market, which has led to their broad acceptance and application in a variety of domains, continued improvements are needed to increase reliability, reduce intrusiveness, and broaden the scope of applicability across real-world tasks and environments.

The advantages harkened by advanced methods and tools, such as those using wireless EEG and eye tracking systems, justify deeper consideration of how they and other like technologies for real-time, operator-centered, online monitoring could serve FMTs. Indeed, as previously argued, ideal solutions appear to involve the combination of multiple vehicle- and operator-centered technologies into hybrid systems. Successful approaches can be seen in those systems that integrate and fuse a variety of data at each level from human physiology and behavior to vehicle motion and mission performance. One such system, which is available for integration on a medium-term timescale, called the Cognitive Assessment Tool Set (CATS) (Operator Performance Laboratory, University of Iowa), uses an approach based on the fusion of multisensory data integrating operator- (EEG, ECG, eye tracking, etc) and vehicle- (motion and mission-specific data) centered technologies that enable the system to adapt to situations of cognitive underload and overload. Originally developed for avionics, this toolset is currently being leveraged into ground vehicle platforms (refer to Pala et al., 2011) and is capable of integrating two or more of most current commercially available technologies.

While the CATS as currently designed makes predictions relative to operator workload, other approaches exist, such as the Atlas Research AR7000 Flagship Mixed Signal Platform, and other information, such as electrodermal activity (e.g., VIGNITION and EDVTCS by J. S. Co. Neurocom) or cardiac activity (e.g., EPIC sensors by Plessey Semiconductors), may be leveraged in a similar architecture for the prediction of fatigue states instead. For example, Ji et al. (2006) have developed a probabilistic Bayesian framework for integrating relatively comprehensive information to predict drowsy driving performance from various sensory data and relevant contextual information of the sort that would be provided by the CATS. Additional information may also be provided by multisensor systems such as the U.S. Army Warfighter Physiological Monitoring System, which has enabled simultaneous measurement of heart rate, respiratory rate, skin temperature, core body temperature, body position, limb movement, sleep activity, ballistic impact events, and instrumented hydration systems on a wearable sensor fusion system to provide a real-time estimate of Soldier state (Friedl, 2007). Similar efforts have been advancing within ARL’s Translational Neuroscience Branch that are continuing to leverage and push the development of a variety of systems, from increasingly miniaturized and softened dry electrode systems coupled with wireless communications protocols to capture medium-density data on high-powered handheld mobile platforms to advanced algorithms enabling online processing and artifact rejection methods necessary to make real-world state assessment ever more reliable and robust across a range of operational conditions (McDowell et al., 2013). Regardless of the specific implementation, a clear message to be taken from the current focus in the domain of emerging FMTs is that the integration of measures on multiple levels, including human physiology and behavior, is an important step on the path toward more robust and reliable vehicle safety systems.

3. Conclusions and Future Directions

Here, we have reviewed the current state of development for FMTs. We have discriminated the currently available and emerging methods into a taxonomy that includes vehicle-centered, operator-centered, and hybrid systems. We have noted that vehicle-centered technologies appear to be the most appropriate for immediate integration with military test-bed vehicles, whereas both operator-centered and hybrid systems, while ultimately promising considerable advantages over vehicle-centered technologies, continue to require additional research and development. Our ultimate conclusion was that hybrid systems that include data from a variety of sources, to include predictive models along with real-time monitoring of both operator and vehicle state, are perhaps the most promising for the delivery of an FMT that is robust across vehicles, environments, and individuals.

Of course, using the information provided in this review, one might make an argument based on current level of maturity that vehicle-centered technologies such as collision detection and lane departure warning systems are sufficient to meet the goals of enhancing survivability in military vehicle contexts and issues of robustness across vehicles and environments can be dealt with in other ways. However, we argue that this type of perspective is focused on too narrow of a vision regarding what contributes to vehicle survivability. Consider, for example, the vehicle commander who has a significant share of the responsibility for vehicle safety through the maintenance of a continual and dynamic sense of situational awareness—failures of which could result in an individual vehicle or convoy being led directly into a compromised position or even a direct engagement with enemies. Without question, fatigue is a significant problem for Soldiers who serve roles other than that of vehicle driver (Belenky et al., 1994; Johnson and Merullo, 1999; Lieberman et al., 2006) and, in those cases, a source of data on which inferences of fatigue may be made is needed.

For military roles that do not involve driving (platoon leader/vehicle commander, gunner), performance variables are often less amenable to direct measurement. Whether the Soldier misses potential threats in the form of enemies or improvised explosive devices is something that is not typically discovered until it is too late and the vehicle or squadron is attacked and potentially even compromised. Be it misinterpreted communications or simply overlooked environmental features in a digital video feed, unlike driving performance errors (weaving in a lane, driving too close to another vehicle), there is no current single, real-time detection method that enable identification of instances when a relevant piece of information has not received adequate attention from the Soldier. As such, if fatigue monitoring is considered an important means of mitigating the types of Soldier performance errors that undermine survivability, then different measures are needed that can be monitored and interpreted for Soldiers in nondriver roles.

A primary advantage of the eventual integration of operator-centered (physiological and behavioral) data is that many of these measures have been shown to be associated with fatigue and decreased performance. Therefore monitoring of operator-centered variables can enable disambiguation of fatigue from other more functional states where performance might also decline (i.e., alert driving but under compromised road conditions, or alert threat scanning but currently attending to a particular high-value target). Of course, additional research is required to define and precisely characterize the relationships between the different types of fatigue and the changes in physiological and behavioral variables. But the main message is that continued research is needed, particularly for understanding fatigue in a variety of operational environments and under different task conditions (driving, threat detection, overwatch). Without the continuation of such efforts, the success of any future FMTs will be significantly limited (Caffier et al., 2003).

In summary, multiple measures need to be considered if a more robust method of fatigue detection is to be developed. An optimal fatigue management system will most likely be a hybrid or multicomponent system (e.g., Heitmann et al., 2001) that exploits biomathematical model predictions, fitness-for-duty testing, and online monitoring (using both operator- and vehicle-centered approaches) integrated to converge on an accurate assessment of the operator's state of alertness and performance capacity (Balkin et al., 2011). Moreover, an ideal FMT should exhibit validity, reliability, generalizability, sensitivity, specificity, adaptability, compatibility, and user acceptability (Balkin et al., 2011; Dinges and Mallis, 1998; Hartley et al., 2000). Policies must be in place regarding how the system is to be used in the operational environment and plans for how to deal with legal/liability issues associated with accidents that may occur as a result of failed detections or false alarms. Most important, the system must be effective in respect to its ability to intervene when potential deficits are identified or anticipated and ultimately it must improve safety by preventing accidents and yet be cost-effective and practical from a business perspective.

The integration of one or more currently available FMTs into an active vehicle safety program for military vehicles will likely enhance vehicle and Soldier survivability with immediate- and medium-term development efforts. FMTs potentially provide a mechanism by which the system may become more informed about the current state of the operator(s), which will enable more accurate and reliable monitoring of Soldier-system performance and more timely mitigations of fatigue-related performance decrements.

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Appendix. Summary Table of Fatigue Management Technologies Available as of July 2013

This appendix appears in its original form, without editorial change.

	FMT Category						Conformance with Military Constraints		
Product	**Category**	**Subcategory**	**Primary Technology**	**Capabilities**	**Fatigue Inference**	**Key Hardware**	**Internal Hardware Mount**	**Steering Wheel or Seat / Belt Modifications**	**Tethers Operator to Vehicle**
Complete Fatigue Mobile Tracking and Data (MTData), Pty. Ltd. www.mtdata.com.au	Hours of Service Monitor	–	Computer	*Monitor compliance with HOS regulations *Record work/rest times *Provide alerts about break non-conformance *Enables tracking and review of 28 day work cycles	None; compliance with work/rest schedule based on operator input/responses	Internal *Dash-mounted unit	Possibly Adaptable	No	No
Optimized Work-schedule & Logistics (OWL™) Pulsar Informatics, Inc. www.pulsarinformatics.com	Hours of Service Monitor	–	Computer	*Evaluate and account for fatigue when building duty schedules *Indentify individuals and groups of individuals that are at elevated risk for fatigue *Quantify effects of schedule changes on fatigue	Full description not available; presume fatigue inference is based on work/rest schedule alone.	None (software can be run on any computer)	No	No	No
Sentinel Transtech www.transtech.net.au	Hours of Service Monitor	–	Computer	*Fatigue status monitoring *Alerts driver before schedule violation occurs *Break compliance monitoring *Communication with remote manager	None; compliance with work/rest schedule based on operator input/responses	Internal *Dash-mounted unit	Possibly Adaptable	No	No
AutoVue Bendix Corporation www.bendix.com	Vehicle-Centered	Vehicle-Environment Monitor	Digital Video	*lane departure warning	Fatigue not inferred; warnings issued based on vehicle risk regardless of cause (i.e. fatigued vs distracted)	Internal *camera *control unit *speakers [opt] *seat vibrators [opt]	Possibly Adaptable	Optional	No
Ctrack Fleet Management Solutions Ctrack Indonesia www.ctrackindonesia.com	Vehicle-Centered	Vehicle-Environment Monitor	GPS Accelerometer	*Record and report vehicle location, speed, and cumulative odometer (per 10 seconds) *Report defined vehicle events, such as harsh braking excessive idling, over-speed, and others *Generation of summary reports, such as daily usage report including first/last stop, total time driven, total distance driven, max daily speed. *Provide visual alerts to driver indicating driving quality/occurrance of harsh driving events	Fatigue not inferred; warnings issued based on vehicle risk regardless of cause (i.e. fatigued vs distracted)	Internal *small driver alerting unit [optional, but needed for providing driver alerts] External *GPS *3-axis/2g force accel- erometer *GSM/SMS or other data transmitter	Yes	No	No

	FMT Category						Conformance with Military Constraints		
Product	Category	Subcategory	Primary Technology	Capabilities	Fatigue Inference	Key Hardware	Internal Hardware Mount	Steering Wheel or Seat / Belt Modifications	Tethers Operator to Vehicle
Mobileye Advanced Driver Assistance Systems MobileEye www.mobileye.com	Vehicle-Centered	Vehicle-Environment Monitor	Digital Video	*lane departure warning *forward collision warning *daylight pedestrian collision warning *intelligent high beam control *speed limit indication	Fatigue not inferred; warnings issued based on vehicle risk regardless of cause (i.e. fatigued vs distracted)	Internal *camera *control unit *speaker	Possibly Adaptable	No	No
SafeTraK Takata Corp. www.safetrak.takata.com	Vehicle-Centered	Vehicle-Environment Monitor	Digital Video	*lane departure warning *erratic driving warning	Fatigue not inferred; warnings issued based on vehicle risk regardless of cause (i.e. fatigued vs distracted)	Internal *camera *control unit *speaker	Possibly Adaptable	No	No
CAPI (Common Alertness Prediction Interface) Jeppesen www.jeppesen.com	Operator-Centered	Biomathematical Model	Computer	*Interface is designed primarily to enable rapidly shifting between multiple models of fatigue for assessment and prediction of fatigue effects in different contexts. *Currently implemented models include the Boeing Alertness Model (BAM) and the Fatigue Audit InterDynamics (FAID) Model	Based on the proprietary Boeing Alertness Model (formerly, the sleep/wake predictor)	None (software can be run on any computer)	No	No	No
Circadian Alertness Simulator (CAS) - Driver Fatigue Model Circadian www.circadian.com	Operator-Centered	Biomathematical Model	Computer	*Prediction of drivers who are at risk for a fatigue- related accident in the coming week *Isolates risk factors and exposes fatigue symptoms to enable proactive coaching and risk management among a fleet of drivers	Based on a two process model of circadian and homeostatic sleep processes, tuned by an individuals sleep wake history either directly observed or estimated from work schedule	None (software can be run on any computer)	No	No	No
CrewAlert Jeppessen www.jeppesen.com	Operator-Centered	Biomathematical Model	Computer	*Scenario planning for investigation of sleep/wake shift scheduling *Record and maintain a sleep history log *Display sleep, fatigue, and predicted fatigue data in summary graphical format *Fatigue prediction based on the Boeing Alertness Model (modifiable with inputs regarding actual, rather than predicted sleep periods) *Perform self-assessment of fatigue using common subjective scales (i.e. Karolinska Sleepiness Scale) or the PVT *Investigates effects of predicted or actual sleep/wake schedules on individual fatigue risks	Based on the proprietary Boeing Alertness Model (formerly, the sleep/wake predictor)	Currently only runs on an Apple iPhone	Possibly Adaptable	No	No

	FMT Category						Conformance with Military Constraints		
Product	**Category**	**Subcategory**	**Primary Technology**	**Capabilities**	**Fatigue Inference**	**Key Hardware**	**Internal Hardware Mount**	**Steering Wheel or Seat / Belt Modifications**	**Tethers Operator to Vehicle**
Fatigue Audit InterDynamics (FAID) **Fatigue Assessment Tool** InterDynamics Pty. Ltd. www.interdynamics.com	Operator-Centered	Biomathematical Model	Computer	*Calculates a quantitative metric to index fatigue exposure *Enables an audit of consequences of work schedule on exposure to fatigue *Predictively assess the impact of factors known to influence fatigue, including work schedule, time on task†, changes in time zone†, and transition time upon return to home time zone† († dependent on software version purchased)	Based on a biomathematical model that incorporates work history (for 7 prior days), the profile of work and breaks including start times and durations, and assumptions about the biologically-imposed limitations of recovery sleep	None (software can be run on any computer)	No	No	No
Fatigue Avoidance Scheduling Tool (FAST) Fatigue Science www.fatiguescience.com	Operator-Centered	Biomathematical Model	Computer	*Accepts inputs regarding duty schedule *Predicts sleep periods and identifies fatigue risk using the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE™) Model *Provides assessment of causal factors for changes in fatigue risk	Does not predict fatigue, but rather Performance Effectiveness assumed to be based on fatigue. Prediction is based on the proprietary Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE™) Model. This includes circadian and homeostatic (sleep inertia, sleep quality, sleep schedule) factors in prediction.	None (software can be run on any computer)	No	No	No
Fatigue Calculator MB Solutions Pty. Ltd. www.fatiguecalculator.com.au	Operator-Centered	Biomathematical Model	Computer	*Estimates likelihood of fatigue risk in one of 5 levels *Graphical display of 24 hour fatigue risk evolution with smartphone App and 48 and 72 hour option available in Windows version *Optional integration with separately-available fatigue manager software, which stores and analyzes fatigue data for both smartphone and Windows versions	Based on the "Prior Sleep/Wake Model", which is based solely on sleep history over two intervals - 24 and 48 hours as well as projected work schedule information.	Internal (platform-dependent) *Handheld unit *mobile device/smartphone *Any windows computer (tablet, kiosk, PC, etc.)	No	No	No

	FMT Category						Conformance with Military Constraints		
Product	**Category**	**Subcategory**	**Primary Technology**	**Capabilities**	**Fatigue Inference**	**Key Hardware**	**Internal Hardware Mount**	**Steering Wheel or Seat / Belt Modifications**	**Tethers Operator to Vehicle**
The System for Aircrew Fatigue Evaluation (SAFE) Alertness Solutions www.alertsol.com	Operator-Centered	Biomathematical Model	Computer	*Generates predicted fatigue levels every 15 minutes *Predict sleep periods, which can be edited when data on actual sleep periods are known *Accommodates time zone changes, circadian infl- uences, and cumulative fatigue *Provides rapid assessment of schedule to identify and quantify potential fatigue risks and problem areas (including 'what if' scenario assessment)	Full description is not available; given capabilities, can presume a model that includes both circadian and homeostatis (time since sleep) components as well as adjustments for time-zone changes and the influence of sleep/wake scheduling.	None (currently only available as online software)	No	No	No
AR7000 Flagship Mixed Signal Platform Atlas Research Ltd. www.atlas-arl.com	Operator-Centered	Online Monitor	Surface Electrophysiology	*Full spectrum surface electrophysiological recording (EEG, EMG, EOG, ECG, GSR, Respiration, Skin temperature, body motion) *Custom applications per customer need. *Existing detection algorithms include: Alertness; Asystole; Apnea; Awareness; Bradycardia; Breathing rate & volume; Cardio- respiratory distress; Cardiovascular shock; Central & obstructive apnea; Drowsiness; Deception; Emotional response; Fall; Heart rate; Muscle tension; Motility; Relaxation; Sleep stages; States of consciousness; Stress; Tachycardia; Unscheduled sleep; Vigilance; Vitality.	Can be designed per customer request using any available information about the operator	Operator-borne *Physiological sensors	Yes (operator-borne)	No	Yes, but likely adaptable
B-Alert X Series Advanced Brain Monitoring Inc. www.advancedbrainmonitoring.com	Operator-Centered	Online Monitor	Wireless Electroencephal-ography (conductive electrode cream required)	*Drowsiness Montoring *Brain-Computer Interaction *Alertness & Memory Profiler *Team Neurodynamics *Cognitive Workload *Additional features for Neuroscience Research (Specific capabilities depend on model and software)	EEG based; Custom software may be integrated	Operator-borne *Flexible sensor array (4, 10, or 24 channels) *DAQ unit Internal *Computer required for real-time applications	Required	No	No
Ctrack Random Reactive Fatigue Warning System Ctrack Indonesia www.ctrackindonesia.com	Operator-Centered	Online Monitor	Visual Signal Toggle Switch	*Produces warnings during attentional lapses	None; Attentional lapses detected by missed probe events (randomly occurring visual warning to be canceled by operator)	Internal *toggle switch *warning light *speaker	Yes	No	No

	FMT Category						Conformance with Military Constraints		
Product	**Category**	**Subcategory**	**Primary Technology**	**Capabilities**	**Fatigue Inference**	**Key Hardware**	**Internal Hardware Mount**	**Steering Wheel or Seat / Belt Modifications**	**Tethers Operator to Vehicle**
Driver Fatigue Monitor MR688‡ Hao Nai Industrial Co. Ltd. www.care-drive.com	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*Driver fatigue monitoring and alerting *Distracted driving detection and alerting (i.e. when driver turns the head or looks awaw from the road for a signficant period of time) *Automatic detection of highway vs. city driving (based on vehicle speed) *Manual and automatic sensitivity adjustment (i.e. uses differential sensitivity for highway vs. city driving speeds)	Percentage of eyelid closure ('PERCLOS') or eye visibility	Internal *Dash-mounted infrared camera	Yes	No	No
Driver State sensor Seeing Macines Inc. www.seeingmachinces.com	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*Drowsiness/distraction event detection *Micro-sleep detection *Driver alerting *Data logging and reporting for after-analyses	Eye gaze detection and percentage closure (PERCLOS)	Internal *Eye-tracking camera *Audio alarm *Seat vibrator	Yes	Yes	No
Driver Vigilance Telemetric Control System (VIGNITION) J.S. Co. Neurocom www.neurocom.ru/en2/	Operator-Centered	Online Monitor	Surface Electrodermal Recording	*Continuous alertness monitoring *Driver alerting to impending hazardous state state *Other driver warning with external lights *Optional engine shut-down command	Measurement of skin conductance based on the Galvanic Skin Response (GSR)	Operator-borne *wristband or ring Internal *Operator warning unit *Vehicle interaction module	Yes	No	No
Engine Driver Vigilance Telemetric Control System (EDVTCS) J. S. Co. Neurocom www.neurocom.ru/en2/	Operator-Centered	Online Monitor	Surface Electrodermal Recording	*Continuous alertness monitoring *Interfaces with active safety systems commanded based on sensed state of operator	Measurement of skin conductance based on the Galvanic Skin Response (GSR)	Operator-borne *wristband or ring Internal *Receiving/secondary signal processing unit *Engine state detection unit interfaced with active safety systems	Yes	No	No
EPIC Sensors Plessey Semiconductors Ltd. www.plesseysemiconductors.com	Operator-Centered	Online Monitor	Semiconductor Sensors	*Physiological sensing (EEG, EMG, EOG, ECG) *Respiration sensing *Motion/gesture sensing *Proximity sensing	Changes in ECG/respiration patterns	Internal or Operator-borne *Semiconductor sensors	Yes (operator-borne)	Optional	No

	FMT Category						Conformance with Military Constraints		
Product	**Category**	**Subcategory**	**Primary Technology**	**Capabilities**	**Fatigue Inference**	**Key Hardware**	**Internal Hardware Mount**	**Steering Wheel or Seat / Belt Modifications**	**Tethers Operator to Vehicle**
EPOC Emotiv www.emotive.com	Operator-Centered	Online Monitor	Wireless Electroencephalography (saline-dampened electrodes required)	*Brain-Computer Interaction *Emotion Monitoring including engagement, boredom, excitement, frustration, meditation *Facial Expression Interpretation	EEG based; Uses correlated variables (boredom, engagement); Custom software may be integrated	Operator-borne *Headset containing a fixed sensor array (10 channels) and onboard DAQ Internal *Computer required	Required	No	No
EyeAlert™‡ Highway Safety Group www.eyealert.com	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*Driver fatigue monitoring and alerting *Distracted driving detection and alerting (i.e. when driver turns the head or looks awaw from the road for a signficant period of time) *Automatic detection of highway vs. city driving (based on vehicle speed) *Manual and automatic sensitivity adjustment (i.e. uses differential sensitivity for highway vs. city driving speeds)	Percentage of eyelid closure ('PERCLOS') or eye visibility	Internal *Dash-mounted infrared camera	Yes	No	No
Mindo National Chao Tung University Brain Research Center www.mindo.com.tw	Operator-Centered	Online Monitor	Wireless, Dry Electroencephalography	*EEG recording *Sleep analysis	None; Custom software may be integrated	Operator-borne *Headset (various materials and sensor configurations; 4, 16 32, or 64 channels) Internal *Device for DAQ and data processing	Required	No	No
Muirhead® Fatigue Warning System Muirhead Protection System Inc. www.rct.net.au	Operator-Centered	Online Monitor	Visual Signal Toggle Switch	*Produces warnings during attentional lapses *Configurable to include parameters for vehicle speed and direction of motion (to prevent alerts during slow maneuvers such as reversing)	None; Attentional lapses detected by missed probe events (randomly occurring visual warning to be canceled by operator)	Internal *toggle switch *warning light *speaker	Yes	No	No
Nap Zapper Zhenjiang Welkin Electronics Co. Ltd. napzapper.com	Operator-Centered	Online Monitor	Accelerometer	*Head nod detection *Adjustable head angle sensitivity (Elite Model only)	None; Alarm based on occurrence of head nod	Operator-borne *specialized device worn over one ear	Yes (operator-borne)	No	No

	FMT Category						Conformance with Military Constraints		
Product	Category	Subcategory	Primary Technology	Capabilities	Fatigue Inference	Key Hardware	Internal Hardware Mount	Steering Wheel or Seat / Belt Modifications	Tethers Operator to Vehicle
OpGuard GuardVant Inc. guardvant.com	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*monitors eye closure, face and head motion in real- time *Identifies fatigue states *Real-time fatigue alerts to both driver and fleet supervisor *Optional video recording with alarms *Optional detection of seat-belt wearing, texting, and reading behavior *Configurable event duration and speed thresholds for alarm triggering *Statistical analysis of shift times, productivity, equipment maintenance, and operator behavior	Percentage of eyelid closure (PERCLOS) and behavioral inference from face and head motion	Internal *integrated sensor, camera alarm, and computer module External/possible adaptable *GPS receiver	Yes	No	No
OptAlert Fatigue Management Glasses OPTALERT www.optalert.com	Operator-Centered	Online Monitor	LED Infrared Emitter Phototransistor Receiver	*Real-time, high-speed monitoring of eyeblink behavior *Determination of fatigue level *Provides driver feedback on fatige level *May be combined with additional tools (behavior- based alertness monitoring; fatigue risk profiling)	Based on an amplitude-velocity ratio of eyelid movement during blinks	Operator-borne *Instrumented eye glasses Internal *Alertness indicator *Alertness monitor [opt]	Yes	No	No
Quasar EEG Dry Sensor Interface 10/20 (DSI 10/20) Quantum Applied Science and Research Inc. (Quasar USA) www.quasarusa.com	Operator-Centered	Online Monitor	Wireless, Dry Electroencephal-ography	*EEG recording *State classification including cognitive workload, engagement, and fatigue *Physiological status monitoring including ECG, skin temperature, motion detection *Calculation of instantaneous heart rate	Based on classification of features extracted from EEG, EMG, ECG, and EOG	Operator-borne *Headset containing a fixed sensor array (21 channels) *Physiological status monitor [opt] Internal *DAQ basestation (wireless/wired) *Computer for real-time applications	Required	No	No
Readiband™ Fatigue Science www.fatiguescience.com	Operator-Centered	Online Monitor	Accelerometer	*Records sleep quality, quantity, and timing *Provides real-time scores indicating estimates of performance, sleep history, and fatigue risk	Accelerometer-based actigraphy	Operator-borne *wristwatch actigraph	Yes (operator-borne)	No	No

	FMT Category						Conformance with Military Constraints		
Product	Category	Subcategory	Primary Technology	Capabilities	Fatigue Inference	Key Hardware	Internal Hardware Mount	Steering Wheel or Seat / Belt Modifications	Tethers Operator to Vehicle
SafetyTrax | DDM[‡]	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*Driver fatigue monitoring and alerting *Distracted driving detection and alerting (i.e. when driver turns the head or looks awaw from the road for a signficant period of time) *Self adjustment of sensitivity to ambient conditions	Percentage of eyelid closure ('PERCLOS') or eye visibility	Internal *Dash-mounted infrared camera	Yes	No	No
Sleep Tracking & Activity Recorder (STAR™) Pulsar Informatics Inc. www.pulsarinformatics.com	Operator-Centered	Online Monitor	Accelerometer	*automatically estimate sleep time & duration, sleep disturbances, insomina, sleep debt and fatigue level, waking activity levels and daily caloric output *Tracks work and sleep schedules along with predicted fatigue levels *Recommends fatigue countermeasures *Provides individualized fatigue education accounting for factors such as extended duty hours, shifted schedules, jetlag, etc.	Full description not available; estimates are based on actigraphy measures (wrist-worn accelerometer) along with, presumably, a biomathematical model	Operator-borne *wrist-worn actigraph	Yes	No	No
Sleep Watcher EX[‡] Exeros Technologies Ltd. www.exeros-technologies.com	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*Driver fatigue monitoring and alerting *Distracted driving detection and alerting (i.e. when driver turns the head or looks awaw from the road for a signficant period of time) *3.5 volt output can be sent to external hardware such as GPS or DVR for fleet management	Percentage of eyelid closure ('PERCLOS') or eye visibility	Internal *Dash-mounted infrared camera	Yes	No	No
Sleeptracker Innovative Sleep Solutions LLC. www.sleeptracker.com	Operator-Centered	Online Monitor	Accelerometer	*Monitor sleep stages *Record and store sleep data *Awaken person at an "optimal" time determined based on inferred sleep stage (alarm in light sleep)	None; Sleep behavior inferred with accelerometer based actigraphy	Operator-borne *wrist-watch	Yes (operator-borne)	No	No
Smart Eye Anti Sleep Smart Eye AB www.smarteye.se	Operator-Centered	Online Monitor	Infrared Camera Computer Processor	*Real-time monitoring of 6 DOF head tracking and 2 DOF gaze tracking *Eyelid closure monitoring *Eye-glasses compensation *Available software for feature analysis	None; basic measures available for fatigue detection (i.e. PERCLOS calcuation, blink rate, etc)	Internal *One or more infrared cameras with infrared emitters *PC for data analysis	Yes	No	No

	FMT Category						Conformance with Military Constraints		
Product	Category	Subcategory	Primary Technology	Capabilities	Fatigue Inference	Key Hardware	Internal Hardware Mount	Steering Wheel or Seat / Belt Modifications	Tethers Operator to Vehicle
SmartCap Edan Safe Pty Ltd. www.smartcap.com.au	Operator-Centered	Online Monitor	Wireless, Dry Electroencephal-ography	*Fatigue status monitoring and real-time display *Operator auditory warning of detected fatigue *Enables centralized monitoring of fatigue levels within an entire fleet	Based on measures derived from detected brain activity; further details not provided	Operator-borne *Specialized baseball hat Internal *Bluetooth-enabled display device	Required / Possibly Adaptable	No	No
SMI Eye Tracking Glasses SensorMotor Instruments GmbH www.eyetracking-glasses.com	Operator-Centered	Online Monitor	Infrared Camera	*High speed eye and head tracking *Interface with a variety of recording platforms (mobile device, PC, etc) *Software packages available for detailed analyses	None; Custom software may be integrated	Operator-borne *Instumented eye glasses Internal *Data logging platform (PC, mobile device, etc).	Yes (operator-borne)	No	No
The Sleep Watch® **Micro II** **Micro III Sleep Watch®** **E-Monitor** Precision Control Design Inc. www.pcdsleepwatch.com	Operator-Centered	Online Monitor	Accelerometer	*Record activity/sleep history *Correct sleep history for off-wrist time *Record ambient temperature, humidity, and solar radiation (E-Monitor Model only)	None; Sleep behavior inferred with accelerometer based actigraphy	Operator-borne *wrist-watch	Yes (operator-borne)	No	No
Fatigue-o-meter PSI Systems www.fatigueometer.com	Operator-Centered	Fitness for duty test	Computer	*Assess an individual's level of fatigue relative to their own baseline determined in a non-fatigued state	Accuracy of judgement and speed of responses in a spatial perception and reasoning task	Software available both over the internet and on certain mobile devices	No	No	No
Psychomotor Vigilance Test (PVT) Pulsar Informatics Inc. www.pulsarinformatics.com	Operator-Centered	Fitness for duty test	Computer	*Meaures changes in cognitive processing speed, attentional lapses, influence of fatigue	Based on response pattern (e.g. reaction times) to the PVT stimuli	None (software can be run on any computer)	No	No	No
The EyeCheck pupillometer MCJ Incorporated www.eyecheck.com	Operator-Centered	Fitness for duty test	Pupillometer	*Screens for fatigue to establish fitness for duty	Measurements of pupil size	Proprietary device (pupillometer), administered prior to duty	No	No	No

	FMT Category						Conformance with Military Constraints		
Product	**Category**	**Subcategory**	**Primary Technology**	**Capabilities**	**Fatigue Inference**	**Key Hardware**	**Internal Hardware Mount**	**Steering Wheel or Seat / Belt Modifications**	**Tethers Operator to Vehicle**
Anti Sleep Pilot Anti Sleep Pilot® www.antisleeppilot.com	Hybrid	Biomathematical Model Fitness-For-Duty Testing Online Monitoring Vehicle-Environment Monitoring	Computer Accelerometer Environment Sensors	*Calculates fatigue level based on 26 factors including: - individual risk profile (age, gender, and 10 others) - fitness for duty (initial fatigue level based on medicine/alcohol intake, sleep history, and 6 others) - driving data (time of day, time since break, and 4 others) *Random attention probes (reaction times then feed into fatigue calculator) *Provides visual/audible alerts when a break is needed (as well as indicates when driving can resume)	Based on a model that incorporates 26 parameters, including individual risk factors, initial fitness for duty fatigue estimate, current fatigue estimate (reaction times to attentional probe), and vehicle behavior.	Internal *Dash-mounted unit or iPhone App	Yes	No	No
Advisory System for Tired Drivers (ASTiD™) Fatigue Management International www.fmig.org	Hybrid	Biomathematical Model Operator-Vehicle Monitor Vehicle-Environment Monitor	Computer Vehicle Sensors	*Prediction of likelihood of falling asleep over 24-hours *Online monitoring of steering behavior and vehicle motion for fatigue determination *Providing real-time alerts of fatigue status to a driver and/or supervisor/fleet manager	Based on predictions from a model that minimally accounts for sleep history and circadian (time of day) effects. Estimates are also derived from measures of steering and vehicle movement patterns that are associated with drowsy or fatigued driving	Internal *Telemetry unit (data collection and transmission) *Speaker or visual indicator for driver alert	Yes	Yes	No
Cognitive Avionics Tool Set (CATS) University of Iowa Operator Performance Laboratory www.hfdata.opl.uiowa.edu	Hybrid	Online Monitoring Operator-Vehicle Monitor Vehicle-Environment Monitor	Surface Electrophysiology Digital Video Computer	*Full-spectrum surface physiological recording (EEG, EMG, ECG, GSR) *Thermal imaging and eye tracking *Environment monitoring (EM Noise, temperature, illumination) *Real-time sensor fusion and synchronization *Visualization *Artifact removal *Data querying *Classification	None; Custom software may be integrated with existing analytics	Operator-borne *Any surface physiology sensors desired Internal *Computer/Interface *Cameras *Environment sensors	Yes	No	No

	FMT Category						Conformance with Military Constraints		
Product	Category	Subcategory	Primary Technology	Capabilities	Fatigue Inference	Key Hardware	Internal Hardware Mount	Steering Wheel or Seat / Belt Modifications	Tethers Operator to Vehicle
Bosch Driver Assistance System Bosch www.bosch-automotivetechnology.com	Hybrid	Operator-Vehicle Monitor Vehicle-Environment Monitor	Vehicle Sensors Digital Video	*driver drowsiness detection *predictive emergency braking *lane keeping assistance and lane departure warning	Steering pattern and vehicle motion and sensor-derived context data (speed, time of day, operator-vehicle interactions, etc.)	Internal *multipurpose camera *steering wheel sensor *visual/audio Indicator *additional vehicle sensors (pedal, yaw rate, wheel speed, etc) External *mid-range radar *long-range radar	Possibly Adaptable	Yes	No

‡ **Systems are based on very similar, if not the same, technology; Appear to provide near identical capabilities with differences due to competitive marketing by multiple vendors**

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
ASTiD	Advisory System for Tired Drivers
AWAKE	Warning According to traffic risK Estimation
CATS	Cognitive Assessment Tool Set
DSS	Driver State Sensor
ECG	electrocardiography
EEG	electroencephalography
EMG	electromyography
FAST	Fatigue Avoidance Scheduling Tool
FMT	Fatigue Management Technology
FRMS	Fatigue Risk Management Systems
GSR	galvanic skin response
NCO	Non-Commissioned Officer
NHSTA	National Highway Traffic Safety Administration
PERCLOS	percentage of eye closure
PVT	psychomotor vigilance task
SAFTE	Sleep, Activity, Fatigue, and Task Effectiveness

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